SPEECH PERCEPTION IN CHILDREN WITH COCHLEAR IMPLANTS FOR

CONTINUA VARYING IN FORMANT TRANSITION DURATION

By

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This dissertation is dedicated to …

My parents, Tony and Anita, who have always been an endless source of love, power, wisdom, motivation, generosity, and inspiration

My sister, Christine, and my brother, Aaron, for their unconditional love, support, friendship, and encouragement

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CHAPTER I

INTRODUCTION

The ability to perceive speech begins prior to birth and continues to develop

throughout childhood (Eisenberg, Shannon, Martinez, Wygonski, & Boothroyd, 2000).

Speech perception involves perceiving the phones, syllables, intonation patterns, and

word boundaries of one's native language, which is necessary for language development.

Children with any degree of hearing loss are at risk for having poor speech perception

and, therefore, struggle to develop typical language skills (Jerger, 2007). Specifically,

children with severe-to-profound hearing loss are at a significantly greater risk than

children with lesser degrees of hearing loss for developing atypical speech and language

due to the lack of auditory input. Despite early identification, intervention and cochlear

implantation in children with profound hearing loss, there is a subgroup of children with

CIs that continues having difficulty in developing age-appropriate language skills (Geers,

2002; Hawker, et al., 2008). To understand the speech perception abilities of children

with CIs, one must consider both the developmental hypotheses of speech perception

(i.e., developmental cue weighting shift model, auditory sensory model, and discontinuity

model) and hypotheses related to speech perception and language disabilities (i.e., higher-level phonetic categorization deficits and auditory temporal deficits).

The purpose of the study was threefold. First, to examine the developmental effects of duration cues by comparing the phonetic boundaries and slopes of TD children to adults on a stop-glide continuum. Second, to examine the effects of duration cues in children with CIs on a stop-glide continuum (i.e., [bɑ] –[wɑ] and [dɑ]-[jɑ]) as they relate to the auditory temporal deficit hypothesis (Tallal, 2000). Third, to explore the impact of auditory sensitivity (i.e., hearing loss versus normal hearing) by comparing the slopes and phonetic boundaries of children with CIs to TD children on a stop-glide continuum. The results of this study provide insight on how a deficit in auditory sensitivity (i.e., hearing loss) impacts speech perception and how speech perception of two stop-glide continua changes developmentally.

CHAPTER II

LITERATURE REVIEW

Developmental Hypotheses of Speech Perception

There is strong evidence to support developmental effects in perception of sounds attended to by children compared to adults such that children attend to different acoustic cues (e.g., dynamic or transition cues) than adults (e.g., static or consonant noise cues) and benefit from louder and longer stimulus presentations (Nittrouer, 2005; Nittrouer & Burton, 2003; Ohde, 1994; Ohde & Haley, 1997; Ohde, Haley, & McMahon, 1996; Ohde & German, 2011). There are three developmental models of speech perception that describe this perceptual process: the developmental cue weighting shift hypothesis, the auditory sensitivity hypothesis, and the discontinuity hypothesis.

The cue weighting shift hypothesis assumes that the developmental changes in speech perception that occur in early childhood are driven by cognitive functions such as attention, linguistic experience, and maturity (Nittrouer, 2002; Nittrouer & Miller, 1997b). As children gain linguistic experience, they gradually decrease their attention to dynamic properties (i.e., formant transitions) that relate to syllable boundaries and increase their attention to static properties (i.e., consonant noise) that relate to the

phoneme as the perceptual unit of their native language (Nittrouer, 2002; Nittrouer & Crowther, 1998; Nittrouer & Miller, 1997a).

Nittrouer (2002) and colleagues have developed a line of research that has primarily focused on the perceptual development of fricatives. A reasonable conclusion from this research is that children and adults use different perceptual strategies when identifying the place of articulation of fricatives. Children weight or pay relatively more attention to the formant transitions than consonant noise to detect the difference between similar syllables such as [si] and [ʃi]. This perceptual strategy focuses more on a unit of speech that is of syllable size rather than phoneme size. In contrast, adults place more perceptual weight on the fricative noise, which focuses on segmental cues of phoneme size. Additionally, research by Ohde and colleagues on the development of stop consonant and vowel perception has demonstrated similar findings to that of the developmental cue weighting shift hypothesis. Their research also revealed that children differ from adults in the acoustic cues emphasized in identification of stop consonants and vowels (Ohde & Haley, 1997; Ohde et al., 1996; Ohde et al., 1995; Ohde & German, 2011). Ohde and Haley (1997) found that dynamic formant transitions were developmentally salient cues for the velar place of stop consonant articulation and that the most prominent cues children use to identify stop consonants were the noise bursts and formant onset frequency cues (Ohde & Haley, 1997; Ohde et al., 1995). Similarities exist between children and adults in identifying vowels (Ohde et al., 1996). However, children's ability to consistently and accurately identify vowels is more variable than in adults. Children rely more than adults on stimulus duration for accurate vowel

identification (Ohde et al., 1996). The most salient cues that children utilize for vowel

perception/identification are formant transition onsets, formant transitions, and formant

transition target frequencies (Ohde & Haley, 1997; Ohde & German, 2011). Differences

in perceptual strategies between children and adults may continue to exist even through

seven or fifteen years of age (Eisenberg et al., 2000; Ohde et al., 1995; Parnell &

Amerman, 1978; Sussman, 2001).

The auditory sensitivity hypothesis of speech perception assumes that

developmental changes in speech perception are linked to the anatomical (i.e., structural

and neurological) differences between children and adults (Sussman, 2001). Schneider

and Trehub (1992) found that neural pathways continue to develop through childhood.

Because children differ anatomically and neurologically from adults, they may require

speech cues of greater amplitude and longer duration (Ohde & Haley, 1997; Sussman &

Carney, 1989) or speech cues that contain greater spectral change than adults to

correctly identify the target acoustic cue (Dorman, Loizou, Fitzke, & Tu, 1998). Sussman

and Carney (1989) found that adults and children differ in their discrimination abilities

for speech stimuli varying in place of articulation and that both adults and children

discriminated longer formant transitions better than shorter ones. However, longer

formant transitions did not benefit children when they were asked to label phonemes that

varied by place of articulation (i.e., [bɑ] vs [dɑ]) such that even the children who were

ten-years-old were less accurate compared to the adults' accuracy (Sussman & Carney,

1989). Eisenberg and colleagues (2000) examined speech recognition with reduced

spectral cues by taking age-appropriate words, sentences, nonsense syllables and digits

and degrading these acoustic signals by filtering them through 4-, 6-, 8- 16-, and 32-bandpass filters. They found that younger children were significantly less accurate than older children and adults in recognizing the speech signal when it was reduced in spectral content. Eisenberg et al. (2000) concluded that as children get older, their ability to recognize a speech signal that has been spectrally degraded approaches that of adults.

From another perspective, the discontinuity hypothesis suggests that the abrupt changes in amplitude and spectral cues play a significant role in perception by signaling boundaries between a consonant and vowel in a syllable (Stevens, 2002). These acoustic discontinuities between consonants and vowels can be referred to as landmark boundaries because they provide critical information in identifying place and manner of articulation. There is some evidence to support that children are able to use acoustic discontinuities to identify place of articulation better than static or dynamic cues (Guillot & Ohde, 2009).

Overall, there is ample evidence indicating differences in the way children and adults perceive speech and utilize acoustic cues in identifying speech sounds. The developmental cue weighting shift hypothesis and the auditory sensory hypothesis of speech perception have been explored in children and adults to explain the differences between the acoustic cues used in identification of place of articulation (Nittrouer & Burton, 2003; Sussman, 2001). Bourland Hicks and Ohde (2005) examined the role of formant transition duration and syllable duration in child and adult speech perception of a stop-glide continuum. They had three different conditions for the stop-glide transition duration continuum (i.e., [bɑ]-[wɑ]). In the first and second conditions formant transitions varied in duration and in the second condition there was an addition of a stop

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burst. In the third condition, the frequency of the formant transitions was varied as appropriate for [bɑ] and [wɑ]. No difference in performance was found in conditions one and two for the adults and children. However, in condition three the children were more sensitive and influenced by the changes in formant transitions such that the children heard more of the stimuli as [wɑ] whereas the adults heard more of the stimuli as [bɑ]. Children's bias towards changes in formant transitions supports the hypothesis that they initially process speech in terms of large syllable-size units as predicted by the developmental cue weighting shift hypothesis.

Comparing the phonetic boundaries and slopes of the TD children to those of adults will allow us to examine any developmental effects. The comparison between the TD children and adults is to determine if the TD children respond differently than adults. It is critical to know whether the TD children in the current study manifest developmental differences. If they do, then these differences must be taken into consideration when interpreting the speech perception abilities of not only TD children but also children who use cochlear implants.

<center>Language Hypotheses of Speech Perception</center>

There are two main language hypotheses, the auditory temporal deficit hypothesis and the higher-level phonetic categorization deficit that explores speech perception and how it relates to language learning in children with normal hearing. These hypotheses attempt to explain why some children have atypical language development (i.e., children

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with specific language impairment- SLI). These two language hypotheses might provide some insight or explanation as to why children with CIs have persistent language learning difficulties.

One explanation for continued language learning difficulty in children who use CIs is that they might have inconsistent representations of auditory stimuli (i.e., phones or phonemes) resulting in poorly-defined phonetic categories. An individual with poorly-defined phonetic categories is not able to consistently differentiate phones containing similar phonological properties or allophonic variations into the correct phonemic category. For example, an individual with poorly-defined phonetic categories might have difficulties distinguishing between the phonemes [b w] because they are unable to utilize manner cues. The phonemes [b] and [w] share voicing (i.e., voiced) and place of articulation (i.e., bilabial) but they vary by formant transition duration (i.e., short [b] stop and longer [w] glide). Since these two phonemes (i.e., [b w]) share two out of three phonological features (i.e., share voicing and place of articulation and differ on consonant manner), it may be difficult for a child with SLI or with hearing loss to consistently identify the phonetic category. This results in poor phonological representations of similar phonemes. On the other hand, an individual with an intact phonological system has a well-defined mental representation of phone categories. This enables the listener to accurately label phones as belonging to different phonemic category.

Speech Perception in Children with Specific Language Impairment

Currently, there are few published studies that have investigated phonetic categories in children with CIs. Therefore, it is important to describe more established perceptual research on phonetic categories prior to reviewing the limited research on children with CIs. There is established research on phonetic boundaries in children with specific language impairment (SLI; Ohde & Camarata, submitted). Studies based on children with SLI might be relevant to children with CIs because children with SLI have unusual difficulty learning and using language despite no known cognitive or neurological anomaly, and yet have adequate hearing and motor abilities (Tomblin, et al., 1997). There is evidence that children with SLI have poorer auditory discrimination and temporal processing (Elliott & Hammer, 1988; Leonard, McGregor, & Allen, 1992) and poorly-defined phonetic categories that contain shallow slopes and phonetic boundaries that are significantly shifted away from TD children (Sussman, 1993, 2001). The slope provides information on how confidently one category ends and another category begins. Children with a steep slope at the phonetic boundary can clearly distinguish between the two phonemes, whereas children with shallow slopes are not able to clearly distinguish between the two phonemes. Children with shallow slopes could have the same phonetic boundary as children with steep slopes (Ohde & German, 2011). This would suggest that the children with the shallow slope can define the boundary between two phonemes but their responses along the continuum are variable and inconsistent. Children with CIs might also have poor auditory discrimination, temporal processing and phonetic boundaries that adversely affect their language development. Research revealing that

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children with SLI define phonetic categories differently from TD children provides a theoretical basis for language learning difficulties in the former, and data from the latter group establishes normative data for performance on stop-glide continua used to assess phonetic boundaries.

There are two prominent explanations for language impairment in children with SLI. One explanation for language impairment in children is that they have a auditory temporal deficit that interferes with the ability to form consistent mental representations of auditory stimuli (Tallal, 1990; Tallal, et al., 1996). Findings that support this explanation suggest that children with SLI have difficulty discriminating and processing brief and/or rapidly changing speech and non-speech auditory stimuli (Tallal, 1990). The other explanation for language impairment in children is that they have deficits at a higher-level phonetic categorization, perhaps involving failure to reliably retrieve the categorical label for a sound stimulus in auditory working memory (Burlingame, Sussman, Gillam, & Hay, 2005; Gathercole & Baddeley, 1990; Sussman, 2001). Findings that support this explanation suggest that children with SLI have difficulty identifying the phonetic boundaries between auditory stimuli. Some children with CIs have continued difficulty learning language despite technological (i.e., cochlear implantation) and educational advances. Having a better understanding of how children with CIs perceive phones might provide additional information on what influences language abilities and why some children have continued language-learning difficulties despite technological and educational advancements.

The conceptualization that children with SLI have greater difficulty with higher-level processing tasks (i.e., identification) compared to lower-level processing tasks (i.e., discrimination) is not surprising as the cognitive loads for each task differ. A discrimination task requires one to be able to make a quick judgment as to whether something is the same or different. Discrimination requires relatively limited linguistic and cognitive resources for a response. In contrast, an identification task requires one to discriminate the sound, store it in short-term memory, retrieve a label for that sound, and then respond. The linguistic and cognitive demands of an identification task are higher and require more resources than sound discrimination. Higher-level processing can be used to describe or characterize the type of cognitive processes involved in identification tasks. However, it is impossible to unequivocally support a higher-level processing deficit because there are multiple contributing factors associated with an identification task (e.g., memory, retrieval, and attention).

There is a controversy regarding support for either the auditory temporal deficit hypothesis or language difficulties experienced by children with SLI as measured by discrimination tasks. Contradictory evidence exists regarding the temporal deficit hypothesis as contributing to language learning difficulties. For example, Leonard, McGregor and Allen (1992) found that children with SLI had difficulty discriminating short stimuli when paired with stimuli of a longer duration. Additionally, Elliott and Hammer (1988) and Elliott, Hammer and Scholl (1989) used discrimination paradigms to investigate temporal acoustic correlates of features (i.e., voice onset time [pɑ]-[bɑ]) and stop consonant place of articulation features (i.e.,[bɑ]-[dɑ]-[gɑ]) in children with SLI and

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in TD children. They found that children with SLI had larger just noticeable differences (JNDs) than TD children, suggesting that children with SLI needed a longer sampling window (i.e., increased duration) to discriminate small differences between sounds.

On the other hand, there is negative evidence regarding the auditory temporal deficit hypothesis as an explanation for language impairment (Bradlow, et al., 1999; Ohde & German, 2011; Shafer, Morr, Datta, Kurtzberg, & Schwartz, 2005; Sussman, 1993). Bradlow et al. (1999) studied the discrimination thresholds between [dɑ] and [gɑ] stimuli in children with SLI and TD children. They found that when the formant transition durations were increased from 40 ms to 80 ms that the children with SLI did not perform better in conditions with longer stimulus duration than shorter duration and that children with SLI and TD had equivalent JNDs. Similarly, Sussman (1993) and Shafer et al. (2005) found no difference between children with SLI and TD children in their performance of discrimination tasks.

There is evidence supporting a model indicating deficits at a phonetic level of processing (i.e., identification) and it is related to auditory working memory for children with language impairment (Burlingame, et al., 2005; Shafer, et al., 2005; Sussman, 1993). Sussman (1993) found that children with SLI had poorer formant transition identification for a [bɑ] to [dɑ] place of articulation continuum than TD children. Furthermore, children with SLI had greater variability labeling phonemes correctly and in placement of phonetic category boundaries than TD children. Shafer et al. (2005) and Datta et al. (2004) found that SLI children's ability to process phonetically-similar vowel sounds

(i.e., [I] versus [ɛ]) was poorer than TD children. Burlingame et al. (2005) provided

support for a model of higher-level language processing deficits for children with SLI.

They showed that children with SLI inconsistently identified (i.e., lower % identification

scores) contrasting syllables (i.e. [bɑ]-[wɑ] and [dɑ]-[jɑ]) within a formant transition

duration continuum.

Speech Perception in Children with Cochlear Implants

It is well documented that children with any degree of hearing loss are at a

disadvantage for acquiring normal speech perception and language abilities, especially

children with severe-to- profound sensorineural hearing loss (Jerger, 2007). Most

children who have such losses are candidates for cochlear implantation, which provides

auditory stimulation for speech and language development. The widespread

implementation of newborn hearing screenings and advances in cochlear implants have

had a dramatic and positive effect on the language achievement of young children with

hearing loss (Geers, Brenner, & Davidson, 2003; Geers, Nicholas, & Sedey, 2003;

Miyamoto, Hay-McCutcheon, Kirk, Houston, & Bergeson-Dana, 2008; Miyamoto,

Houston, Kirk, Perdew, & Svirsky, 2003; Nicholas & Geers, 2006b; M. A. Svirsky,

Robbins, Kirk, Pisoni, & Miyamoto, 2000). Prior to cochlear implantation, children with

severe-to-profound hearing loss had significant perceptual deficits, which adversely

affected their speech and language development. If a child does not have access to

speech, then he/she will be unable to form appropriate phonological representations and

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will be unable to provide consistent labels to phones and phonemes, which combine together to make words.

It has been well documented that 50% of school-age children with CIs achieve age-appropriate scores on omnibus measures of language (Geers, 2002; Geers, Nicholas, et al., 2003; Inscoe, Odell, Archbold, & Nikolopoulos, 2009; Sarant, Holt, Dowell, Rickards, & Blamey, 2009). However, an omnibus measure of language only provides a broad picture of language abilities. Numerous studies have indicated that both older and younger children with CIs have severe receptive and expressive deficits in the area of syntax and grammar (Geers, Nicholas, et al., 2003; Nicholas & Geers, 2006b; Nikolopoulos, Dyar, Archbold, & O'Donoghue, 2004; Spencer, Barker, & Tomblin, 2003). The receptive and expressive language abilities of some children with CIs are often well below age expectations (i.e., 1-3 SDs below test means), even for children who are implanted by one year of age (Miyamoto, et al., 2003; M. Svirsky, Teoh, & Neuburger, 2004).

It has been well documented that children with CIs can make rapid auditory gains in speech perception and language development within the first year of cochlear implant experience (Nicholas & Geers, 2006a; Robbins, Burton, Osberger, Zimmerman-Phillips, & Kishon-Rabin, 2004; M. Svirsky, et al., 2004). Furthermore, children who are implanted prior to two years of age can have better auditory and word recognition skills than children who are implanted after two years of age (Hassanzadeh, Farhadi, Daneshi, & Emandjomeh, 2002; Nicholas & Geers, 2006a; Robbins, et al., 2004; M. Svirsky, et al., 2004). Svirsky et al. (2004) stated that not only do children who are implanted within the

first two years of life have better auditory skills and language development, they also have a vocabulary growth trajectory (i.e., rate of growth) that is five and half months faster than that of children who are implanted after two years of age. Children who receive early implantation (i.e., prior to two years of age) have overwhelmingly better chances of acquiring language skills that are similar to TD children.

The studies mentioned above used words to measure the speech perception abilities of children with CIs. Measuring speech perception using words, as opposed to phones and/or phonemes, not only allows one to gain information about how children with CIs process words, but also provides information about overall language abilities. However, in attempting to understand and explain the language development in children with CIs, exclusively using words to measure speech perception does not provide information regarding the role of the phonological representation of phonemes.

There is limited research investigating the speech perception of phonemes in children with CIs. However, there is research investigating the speech perception of children with hearing loss who use hearing aids. Research by Nittrouer and Burton (2003) focused on the speech perception and language processing abilities in children with hearing loss who use hearing aids. They found that children with hearing loss did not attend to acoustic properties of formant transitions and fricative-noise spectra as much as the children with normal hearing (Nittrouer & Burton, 2003). Furthermore, children with hearing loss required longer voice onset times to identify the difference between [tɑ] and [dɑ] stimuli (Nittrouer & Burton, 2003). The children with hearing loss who had better language weighted the fricative noise, as did the children with normal

hearing, whereas the children with hearing loss who had poor language abilities attended more to the formant transition (Nittrouer & Burton, 2003).

The research investigating developmental hypotheses of speech perception in children with CIs is limited. A recent study by Guillot and Ohde (2009) investigated the phonemic sensitivity of TD children and children with CIs using nasal consonants in a task that was based on the discontinuity hypothesis. As mentioned earlier, the discontinuity hypothesis of speech perception suggests that abrupt changes in amplitude and spectral cues play a significant role in perception by signaling boundaries between a consonant and vowel in a syllable. For example, amplitude changes occur in low and high frequency ranges for labial and alveolar nasals, respectively (Oakey & Ohde, 2007). It is the perception of spectral change that provides critical information in identifying place of articulation of phones (Stevens, 2002)

Guillot and Ohde (2009) found that TD children were more accurate in indentifying place of articulation for nasal consonants when the stimulus segment contained a spectral discontinuity cue. This supports the importance of the spectral discontinuity as an explanation for nasal perception in TD children. Children with CIs were significantly less accurate in identifying short duration nasal segments that varied by place of articulation (i.e., 50 ms murmur, 50 ms transition, 25 ms murmur + 25 ms transition) compared to the TD children.
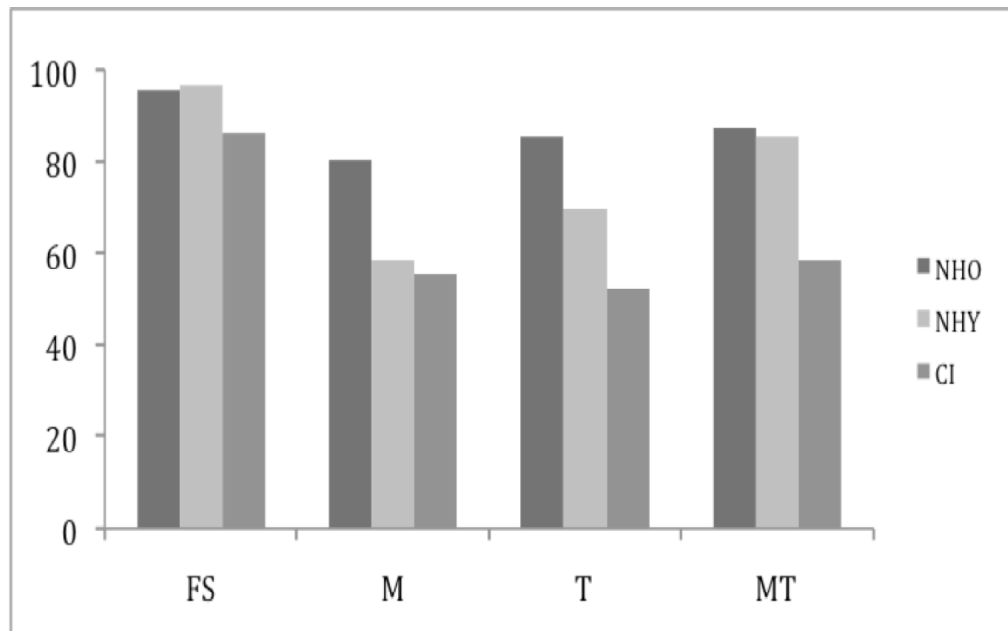
Figure 1: The performance of the children who use cochlear implants compared to the performance of the older children and younger children

However, children with CIs were comparable in performance to the TD children in the full syllable condition, which was the entire duration of the syllable (i.e., full syllable 300 ms versus 50 ms nasal segment). It was predicted that children with CIs would be able to utilize the information in the acoustic segment that contained the abrupt change in amplitude (i.e., 25 ms murmur + 25 ms transition) to identify the place of articulation because it is rich in acoustic cues for place of articulation. This prediction, however, was not supported. It might be that the abrupt change from the consonant to the vowel was not a salient enough cue for identification by children with CIs.

Though children with CIs did not support the discontinuity hypothesis when considered as a group, performance within this group was highly variable. Therefore,

data were reexamined based on the composite language score. Children with language scores within the normal range more accurately identified (70%) place of articulation in the condition containing the discontinuity than the children with lower language scores (49%). The nature of the relationship between speech perception and language development is somewhat unclear.
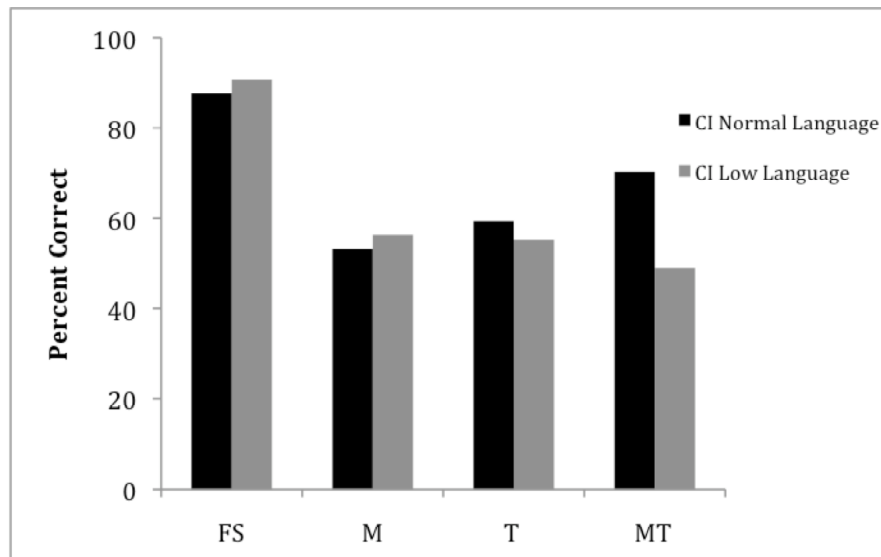
Figure 2: The performance of the children who use cochlear implants divided into low-language and normal-language.

Hawker, Ramirez-Inscoe, Bishop, Twomey and O'Donoghue (2008) conducted a study that investigated language impairment in children with CIs. They found that there is a disproportionate amount of language impairment in children with CIs- a language impairment that cannot be solely attributed to their hearing loss because they received early identification, early amplification and early intervention (Hawker, et al., 2008). The

limited data provided by Guillot and Ohde (2009) suggest that there might be other

influences affecting language development in children with CIs than previously reported,

such as poor phonological representation similar to that reported for children with SLI.

Statement of Problem

Prior to receiving a cochlear implant, children with severe-to-profound hearing

loss experience a disruption in auditory input, which adversely affects their speech and

language development, including the development of speech perception (Guillot & Ohde,

2009). Currently, there is limited research regarding the development of speech

perception in children with CIs. The impact of auditory deprivation on speech perception

is unclear because of the limited research available examining the development of phone

perception in children with CIs. There are various acoustic properties (e.g., dynamic

cues, static cues, duration cues, amplitude cues, voicing cues) that may influence phone

perception. Exploring the influence of hearing loss on the development of phoneme

perception will provide additional insight on how a sensory deficit (i.e., hearing loss)

affects speech perception development.

There are two hypotheses attempting to explain the language learning difficulties

in children with SLI. One hypothesis suggests that the basis for language learning

difficulties in children with SLI is a temporal deficit, which makes it difficult to process

short or rapid changing duration cues (Tallal, 1990, 2000). Another hypothesis suggests

the basis for language learning difficulty in children with SLI is a higher-level processing

deficit, which makes it difficult to categorize and label phones (Burlingame, et al., 2005; Sussman, 1993). The auditory temporal deficit hypothesis can be examined behaviorally by systematically varying the duration of speech stimuli, whereas the higher-level processing deficit is difficult to examine behaviorally because it is impossible to know what is influencing one's ability to categorize and label phones.

Researchers have attempted to explain the reason for language impairment in children with normal hearing by hypothesizing a deficit in speech perception. There is substantial research supporting the poorer performance of SLI children on a variety of speech perception measures compared to TD children (Burlingame, et al., 2005; Ohde & German, 2011; Leonard, et al., 1992; Sussman, 1993, 2001). For example, there is evidence supporting that children with SLI have shallow slopes on a stop-glide continuum, had less consistent responses along the entire continuum, and difficulty with rapid duration cues compared to TD children (Burlingame, et al., 2005; Tallal, 1990, 2000). Children with SLI and children with CIs both experience language-learning difficulties, whether it is due to a hearing loss or a faulty language system. Therefore, it is hypothesized that children with CIs will have shallow slopes on a stop-glide continuum and difficulty with the short duration end of the continuum (i.e., stop consonant versus glide consonant) compared to TD children, which is similar to the findings seen in children with SLI.

The purpose of the study was threefold. First was to examine the developmental effects of formant transition duration cues by comparing the phonetic boundaries and slopes of TD children to adults on a stop-glide continuum. Comparing the performance of

the TD children to findings for adults will allow us to examine any developmental effects. It is critical to know whether the TD children in the current study manifest developmental differences. If they do, then these differences must be taken into consideration when interpreting the speech perception abilities of not only TD children but also children with CIs. Based on the developmental cue weighting shift hypothesis and findings from Bourland Hicks and Ohde (2005), it is predicted that the TD children will be more sensitive and influenced by the changes in formant transitions such that the children hear more of the stimuli as glides whereas the adults hear more of the stimuli as stops. Additionally, it is predicted that the TD children will have shallower slopes compared to the adults because they have less linguistic experience according to the developmental cue weighting shift hypothesis and a less mature neurological system according to the auditory sensitivity hypothesis.

The second purpose was to examine the effects of formant transition duration cues in children with CIs on a stop-glide contrast (i.e., [bɑ] –[wɑ] and [dɑ]-[jɑ]) as related to the auditory temporal deficit hypothesis (Tallal, 2000). The duration of the formant transition differs between the stop (i.e., [b] and [d] short formant transitions) and the glide consonants (i.e., [w] and [j] longer formant transitions). There are well-established behavioral data for adults, TD children, and children with SLI using this stop-glide paradigm. In addition, the acoustic properties in a stop-glide paradigm are phonetically relevant and a continuum can be made between the stop and glide by systematically changing the duration of the transition. Using two different continua, such as [bɑ]- [wɑ] and [dɑ] - [jɑ] provides information about generalization across place of articulation and

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perhaps information about duration cues related to specific phones. For example, the phones [bɑ] and [wɑ] are relatively shorter in duration compared to the phones [dɑ] and [jɑ], which might provide additional information regarding duration. An identification task allows us to evaluate how children with CIs and TD children attach phonetic labels to these signals. The auditory temporal deficit hypothesis (Tallal, 2002) predicts that the stop-end of the continuum will be perceptually more difficult (i.e., performance will be worse) compared to the glide-end of the continuum (i.e., performance will be better). Therefore, it is predicted that children with CIs will perform poorly at the stop-end of the continuum compared to the glide-end of the continuum.

The third purpose of this study was to explore the impact of auditory sensitivity (i.e., hearing loss versus normal hearing) by comparing the slopes and phonetic boundaries of children with CIs to TD children on a stop-glide continuum. Language acquisition occurs throughout early childhood and is a complex process that involves the relationship between speech perception and speech production. There is evidence to support that young children attend to formant transitions when identifying place of articulation (i.e., [m] vs [n]) and consonant manner (i.e., [b] vs [w]; Ohde & Haley; Ohde et al., 1995). However, there is little research investigating the impact of a sensory deficit (i.e., hearing loss) on speech perception development in children with CIs. By using a stop-glide continuum, one is able to compute both the slope of the stop-glide continuum and the phonetic boundary between two phonemes. The slope provides information on how confidently one decides where one category ends and another category begins. The phonetic boundary provides information on one's ability to conceptualize phonetic

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categories by deciding relatively abruptly when one sound category ends (e.g., [b]) and another begins (e.g., [w]). Children with a steep slope at the phonetic boundary can clearly distinguish between the two phonemes. It was predicted that children with CIs would have shallower slopes and would be less confident about the phonetic boundaries compared to TD children. Additionally, children with CIs would require longer duration cues such that their phonetic boundary would be closer to the glide end of the continuum versus the stop end of the continuum.

In summary, it is first important to understand normal development, especially when examining an atypical population. Comparing the performance of the TD children to that of the adults provides a developmental contrast and a basis for interpreting the performance of the children with CIs on the stop-glide continua. It is established that children with CIs who have better speech perception have better language abilities than children with CIs who have poorer speech perception (Geers, 2002; Spencer et al., 2003). However, there is limited research exploring the speech perception of phones in children with CIs. The auditory temporal deficit hypothesis provides evidence to support that children with SLI have poorer speech perception (i.e., processing rapid acoustic cues) compared to TD children (Tallal, 1990). We can systematically test the auditory temporal deficit hypothesis in children with CIs by using a stop-glide continuum that systematically varies the duration of formant transitions. This resulted in an understanding of how children with CIs perceive sound features based on duration cues related to stop and glide phonemes. Based on the three purposes of this study, the following research hypotheses were be addressed:

a. Typically-developing children will be more sensitive towards changes in formant transitions (i.e., hear more of the stimuli as glides) and have shallower slopes compared to the adults on a stop-glide continuum.

b. Children with CIs will be more accurate in identification at the glide-end of the continuum compared to the stop-end of the continuum as predicted by the auditory temporal deficit hypothesis (Tallal, 1990, 2000).

c. If auditory sensitivity adversely impacts speech perception, then children with CIs will have shallower slopes and will have phonetic boundaries that occur closer to the glide-end of the continuum compared to TD children.

CHAPTER III

METHODS

Participants

The participants were eight adults between the ages of 18 to 35 years, eight TD children between the ages of five to eight years, and seven children with CIs between the ages of five to eight years. All the children in the study had a nonverbal intelligence quotient above 85 on the *Leiter International Performance Scale-Revised* (Roid & Miller, 1997) and were monolingual speakers of English. The children with CIs were matched for age and gender to TD children. The children with CIs ranged in age from 5;3 to 8;11 with a mean of 6;8 (SD= 19.1 months) and the TD children range in age from 5;1 to 8;11 with a mean of 6;5 (SD= 18 months). There were two male and five females in the CIs group and three males and five females in the TD group.

The children with CIs had at least three years experience of consistent usage of the cochlear implant (i.e., wears cochlear implant for at least eight hours on a daily basis) and were identified with hearing loss by 12 months of age and received an implant by two years of age. Five of the seven children with cochlear implants were bilaterally implanted and the two children with unilateral implants wore a hearing aid on the opposite ear. The children received early intervention by 12 months of age and were enrolled in speech-language therapy and/or oral habilitation at the time of the study. All the participants in the study were patients of the Audiology Clinic at the Vanderbilt Bill

Wilkerson Center. Children with auditory neuropathy, intellectual disabilities, autism, or

any syndrome that has associated cognitive disabilities (e.g., Down syndrome or

DiGeorge syndrome) were excluded from participating in the study.

	Gender	Age (yrs;mth)	Non-verbal IQ	PPVT	EVT	OWLS Composite	Age Id (mths)	Age of CI (mths)	# of CIs
Children with Cochlear implants									
CI01	M	5;10	115	94	102	87			1
CI02	F	5;11	115	89	93	86			2
CI03	F	6;7	115	75	103	84	12	20	2
CI04	F	5;4	109	94	99	79	10	12	2
CI05	M	8;11	111	101	96	93	1	12	1
CI06	F	8;11	115	106	99	104	9	14	2
CI07	F	5;3	103	76	74	71	1	13	2
Mean		6;8	111.9	90.7	95.1	86.3			
Typical Development Children									
TD01	F	5;9	109	140	117	125			
TD02	M	8;8	119	132	112	113			
TD03	F	5;2	85	75	68	78			
TD04	F	5;8	119	150	120	107			
TD05	M	5;9	97	109	102	92			
TD06	M	6;7	129	111	114	107			
TD07	F	5;11	107	106	110	92			
TD08	F	5;1	121	123	125	107			
Mean		6;5	110.8	118	108.5	103			

Table 1: Participant Demographics
Non-verbal IQ = Leiter; PPVT= Peabody Picture Vocabulary Test; EVT= Expressive Vocabulary Test;
OWLS= Oral and Written Language Scales

The TD children were recruited from the Vanderbilt community. The adults were

recruited from Hearing and Speech Sciences Graduate program at Vanderbilt and the

general population at Vanderbilt University. All children and adult participants had

normal hearing sensitivity at or better than 20 dB for the frequencies of 500, 1000, 2000 and 4000 Hz bilaterally and were screened prior to each experimental session.

Stimuli

Two manner of articulation continua, [bɑ] - [wɑ] and [dɑ] - [jɑ] were used for this study and were modeled after the stimuli used in Burlingame et al. (2005). The stimuli were created using a HLSyn, which is an updated form of the Klatt cascade/parallel formant synthesizer (Klatt, 1980; Stevens & Bickely, 1991). The sampling rate was 10 kHz, and the output was low-passed filtered with a cutoff frequency of 4 kHz. In both continua, F1 started at 250 Hz at the onset of the transition, and then ended at 750 Hz at the offset of the transition, and remained constant at 750 Hz for the remaining stimulus. For each stimulus the total duration was 350 ms. For the [bɑ] - [wɑ] continuum, the F2 transition started at 650 Hz and ended at 1200 Hz, and the F3 transition started at 2000 Hz and ended at 2400 Hz. For the [dɑ] - [jɑ] continuum, the F2 transition began at 1700 Hz and ended at 1200 Hz and the F3 transition began at 2700 Hz and ended at 2400 Hz. The steady-state values of F2, F3, F4, F5 and F6 for both continua were 1200 Hz, 2400 Hz, 3250 Hz, and 4990 Hz, respectively. Each continuum contained nine stimuli. The transition durations for the [bɑ] - [wɑ] continuum ranged from 15 ms to 95 ms in 10 ms steps and the [dɑ] - [jɑ] continuum ranged from 25 ms to 121 in 12 ms steps.

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The endpoint productions of [bɑ] - [wɑ] and [dɑ] - [jɑ] served as control stimuli within the continuum and were used during training and as a means of monitoring for reliable responses during the experimental conditions. All of the stimuli were presented ten times each for a total of 180 stimuli (i.e., 2 continuum x 9 steps x 10 presentations).

Procedures

The children were administered the *Leiter International Performance Scale-Revised* (Roid & Miller, 1997), *Oral and Written Language Scales* (Carrow-Woolfolk, 1995; OWLS), the *Peabody Picture Vocabulary Test* (Dunn & Dunn, 1996; PPVT-III), the *Expressive Vocabulary Test* (Williams, 1997; EVT), and the *Arizona Articulation Proficiency Scale* (Fudala, 2000) to evaluate their speech and language abilities.

All training and testing was conducted in a quiet room and the experimental conditions were conducted in a sound-treated booth via loudspeaker at a comfortable listening level of approximately 68 dB SPL (Guillot & Ohde, 2009). The loudspeaker was placed at zero degrees azimuth at approximately one meter from the participant. Each participant was tested in his/her best listening condition (e.g., unilateral or bilateral cochlear implants or cochlear implant in one ear and hearing aid in the other ear). The stimulus presentation and data collection were controlled by a computer. A two-alternative forced-choice (2AFC) testing paradigm was utilized.

All participants were instructed to respond to each stimulus by pressing a button or pointing to a picture of a puppet that corresponded to the CV stimulus presentation and

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encouraged to guess in instances of uncertainty. Adult listeners were seated in front of a response box with two buttons labeled "d" and "j" or with "b" and "w". The adults responded by pressing one of these buttons. Children responded by naming and pointing to a photograph of one of two puppets for each continuum. The puppets were named to represent each consonant in the varying CV syllable combinations (i.e., [bɑ] [wɑ] [dɑ] [jɑ]).

One experimenter was in the booth with the child to monitor the attention level and to record the child's responses by pressing the corresponding buttons on the response box. The child sat facing the loudspeaker and the experimenter sat facing the child to the right (Guillot & Ohde, 2009).

Training

A sequence of training sessions was used to obtain reliable performance. The children participated in an initial period of formal practice in order to help them associate the names with the pictures of the puppets to be used in the following speech perception test. The experimenter modeled labeling the picture of the puppets for the child. The child was asked to say the name of the puppet and point to the corresponding picture. Next, the child was required to repeat the name of the puppet produced via live voice by the experimenter and point to the photograph of the corresponding puppet. When the child was able to make two correct identifications of both photographs of the puppets presented consecutively, the training proceeded to stimulus presentation via loudspeakers. The

experimenter provided corrective feedback as needed during the training session. The

participants were required to correctly identify at least eight of 10 endpoint syllables

during the training before proceeding to the experimental conditions. The training was

repeated until the child met the criteria. A majority of the children with normal hearing

required only one presentation of the training, whereas the children with CIs often

required two presentations of the training to meet the criteria.

Experimental Testing

The participants heard each stimulus from both continua ten times for a total of

180 stimuli (i.e., 9 stimuli x 2 continua x 10 presentations = 180). The 180 stimuli were

divided into four conditions (i.e., 2 [bɑ] - [wɑ] conditions and 2[dɑ] - [jɑ] conditions) so

that there were 45 stimuli per condition. Using the procedures presented in the

Burlingame et al. (2005) study, the presentation order was fixed across all participants so

that they first received the [bɑ] - [wɑ] continuum followed by the [dɑ] - [jɑ] continuum.

For the adults and children, the stimulus presentation was adjusted to the individual's

response rate, so that no stimulus was presented until the individual had responded to the

previous one. The examiner was in the room with the child during the testing and

recorded the child's response (i.e., verbally saying the syllable and pointing to the

photograph of the corresponding puppet) by pushing the corresponding button. If there

was a discrepancy, the experimenter asked the child to repeat the response. If there

continued to be a discrepancy, the examiner recorded the child's manual response. The

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participants were prompted to respond to all presentations. The children were reinforced

using stickers and verbal praise during the experimental condition. The children received

a small toy or book at the end of each session and an age-appropriate book at the end of

their participation in the study.

Analyses of the Findings

The percent of [bɑ] and [dɑ] responses were transformed to *z scores* for each

participant. Using the *z scores* against the stimulus duration, the intercepts from a

regression calculator (Ashmead, 2010) yielded slope values for the continua and phonetic

boundary values, which represents the 50% point between the [bɑ] – [wɑ] categories and

[dɑ] – [jɑ] categories. To evaluate main effects (i.e., place of articulation and group) and

interactions (i.e., place of articulation x group) between the groups and the phonetic

boundaries and the slopes, two repeated measures analyses of variance (ANOVAs) were

used to analyze the data. Both analyses included the between factor of group (i.e.,

children with CIs vs. TD children vs. Adults) and the within factor was place of

articulation (i.e., labial vs. alveolar). In the first analysis, the dependent variable was the

phonetic boundary of the continua. In the second analysis, the dependent variable was the

slope of the continua. Planned univariate ANOVAs were performed on the slope and

phonetic boundary within the two continua (i.e., [bɑ] – [wɑ] and [dɑ] – [jɑ]). The fixed

factor was group (i.e., children with CIs vs. TD children vs. Adults) and the dependent

factors were slope and phonetic boundary. Linear contrasts were used as follow-up

measures to explore significant group differences within the dependent variable. Paired

sample t tests were used to compare the mean correct performance for the endpoints of

TD children and children with CIs.

CHAPTER IV

RESULTS

The first research hypothesis to be addressed was: Typically-developing children will be more sensitive towards changes in formant transitions (i.e., hear more of the stimuli as glides) and have shallower slopes compared to the adults on a stop-glide continuum. A repeated measures ANOVA for phonetic boundary revealed a significant main effect for place of articulation (i.e., bilabial vs. alveolar), $F(1,20)= 9.047$, $p= .007$, but not for group (i.e., adult versus TD children versus children with CIs), $F(2,20)= 2.794$, $p= .085$. There was no interaction between the groups and place of articulation, $F(2,20) = 2.58$, $p= .101$, which suggests that there was no difference in the patterns of performance across the two continua. Two univariate ANOVAs were conducted to evaluate simple main effects for each continuum individually. The fixed factor was group (i.e., adult, TD children and children with CIs) and the dependent factor was place of articulation (i.e., [bɑ] – [wɑ] or [dɑ] – [jɑ]). The univariate ANOVAs revealed a significant difference for the phonetic boundary of the [bɑ] – [wɑ] continuum, $F(2,20)= 6.085$, $p= .009$ but no difference for the phonetic boundary of the [dɑ] – [jɑ] continuum, $F(2,20)= 1.028$, $p= .376$.
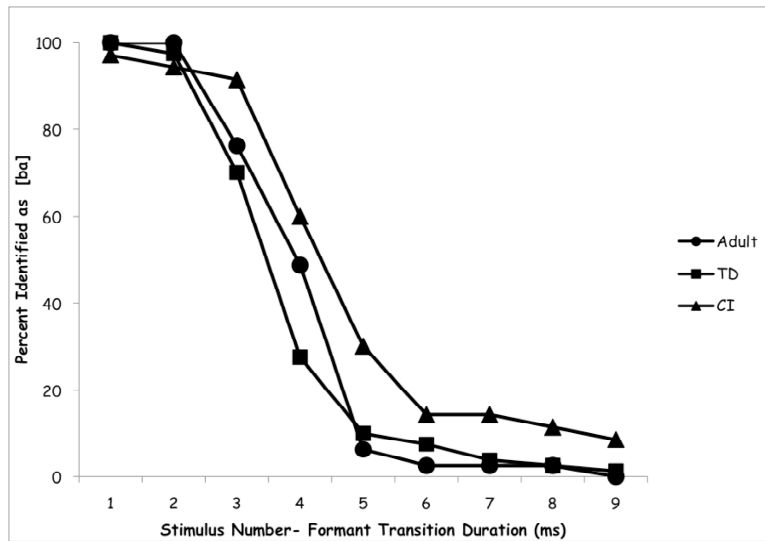
Figure 3: Typically-developing children and cochlear implanted children compared to adults on the [ba- wa] continuum

As seen in Figure 3, the difference in phonetic boundary on the [bɑ] – [wɑ] continuum among the TD children, children with CIs and adults was evident whereas, on the [dɑ] – [jɑ] continuum there was no difference on phonetic boundary between the TD children, children with CIs and adults.
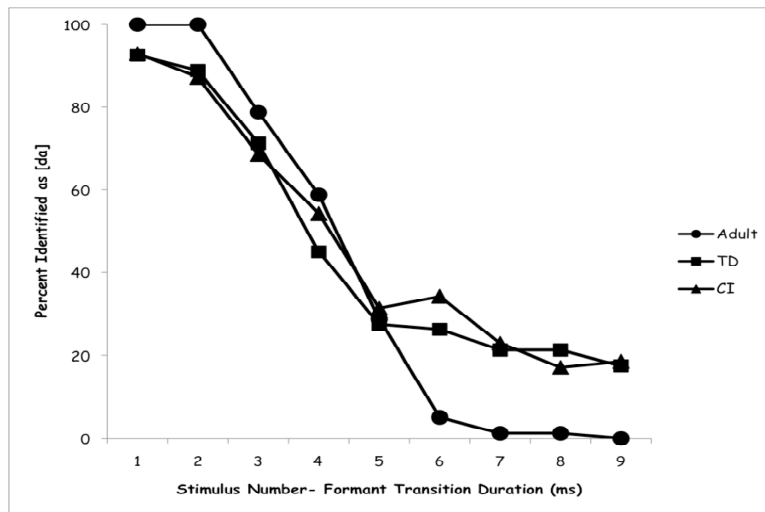

Figure 4: TD children and CI children compared to Adults on the [da- ja] continuum

To follow-up on the univariate ANOVAs, linear contrasts were used to explore the group differences for the [bɑ] – [wɑ] continuum. However, the [dɑ] – [jɑ] continuum was not explored for further group difference since there was not a significant effect of group on the simple main effect. There were significant differences on the phonetic boundaries of the [bɑ] – [wɑ] continuum between the adults compared to both TD children, $F(1,20)= 10.642$, $p= .005$ and children with CIs, $F(1,20)= 24.101$, $p< .001$. See Figure 3 for group comparisons. The TD children's phonetic boundary for the [bɑ] –[wɑ] continuum occurred closer to the stop-end of the continuum and perceptually heard more glides than stops compared to the adults' phonetic boundary. This suggests that the TD children were more influenced by the changes in formant transitions, which supports previous findings by Bourland Hicks and Ohde (2005) and the cue weighting shift hypothesis. Bourland Hicks and Ohde (2005) found that children were more sensitive and influenced by the changes in formant transitions such that the children heard more of the stimuli as [wɑ] compared to the adults. Conversely, the children with CIs' phonetic boundary for the [bɑ] –[wɑ] continuum occurred closer to the glide-end of the continuum and heard more stops than glides compared to the adults' phonetic boundary. This suggests that the children with CIs needed considerably longer formant transitions to switch from the stop consonant to the glide consonant. Burlingame et al. (2005) found similar findings in children with SLI in that their phonetic boundary was biased towards the glide-end of the [bɑ] –[wɑ] continuum.

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Even though there was no difference between the phonetic boundary for the [dɑ]-

[jɑ] continuum, the TD children and children with CIs' performance was more variable

compared to the adults. The phonetic boundaries for the TD children and children with

CIs ranged respectively from 2.8 to 6.2 (m= 4.5, SD= 1.05) and 3.3 to 5.8 (m= 4.8, SD=

.093), whereas the adults ranged from 3.2 to 4.9 (m= 4.1, SD= 0.69). In general, the

performance on the [dɑ]-[jɑ] continuum was more variable across the participants

compared to the performance on the [bɑ] –[wɑ] continuum, especially for both groups of

children. Burlingame and colleagues (2005) had similar findings on the [dɑ]-[jɑ]

continuum in their study. Anecdotally, the adults reported that perceptually the [dɑ]-[jɑ]

continuum was more challenging than the [bɑ] –[wɑ] continuum. Additionally, a majority

(86%) of the children required at least two repetitions of the training to meet the 80%

criteria to continue with the experimental condition, as did several of the adults.

A repeated measures ANOVA for slope revealed a main effect for place of

articulation (i.e., bilabial vs. alveolar), $F(1,20)= 10.346$, $p= .004$, and a main effect for

group, $F(2,20)= 7.122$, $p= .005$. There was no interaction between group and place of

articulation, $F(2,20) = .949$, $p= .404$, which suggests that there was no difference in the

patterns of performance across the two continua. Two univariate ANOVAs were

conducted for each continuum to evaluate simple main effects. The fixed factor was

group (i.e., adult, TD children and children with CIs) and the dependent factor was place

of articulation. The simple main effect for slope was significant for both the [bɑ] – [wɑ]

continuum, F(2,20)= 6.633, p= .006 and the [dɑ] – [jɑ] continuum, F(2,20)= 3.676, p= .04. To follow-up on the simple main effects, linear contrasts were used to explore the group differences for the slopes of the [bɑ] – [wɑ] and [dɑ] – [jɑ] continua. For the [bɑ] – [wɑ] continuum, there were significant differences between the adults and TD children, F(1,20)= 12.779, p=. 002 and children with CIs, F(1,20)= 58.091, p< .001. For the [dɑ] – [jɑ] continuum, there were significant differences between the adults and TD children, F(1,20)= 35.15, p< .001 and children with CIs, F(1,20)= 28.27, p< .001. The TD children and the children with CIs' slopes for both continua were shallower compared to the adults. This suggests that the children are less confident in defining the phonetic category between the two phonemes. This is not surprising since children are not as developed neurologically or linguistically as adults. Young children initially have very defined phonetic categories in that they are likely to have less tolerance for slight variations or changes in the perception of phones such as the variation in formant transition duration in both the continua of the current research. This would result in a larger range of ambiguous responses (e.g., responses around the 50% mark) for the children compared to the adults. This is because the stimuli in the middle of the continuum are less distinct compared to the end points. As children start to mature neurologically and linguistically they begin to have more tolerance within each phonetic category and allow allophonic variations.

The second research hypothesis to be addressed was: Children with CIs will be more accurate in identification at the glide-end of the continuum compared to the stop-end of

the continuum as predicted by the auditory temporal deficit hypothesis (Tallal, 1990, 2000). The auditory temporal deficit hypothesis predicts that children with SLI or language-learning difficulties will have better (i.e., higher percent correct) performance at the glide-end of the continuum compared to the stop-end of the continuum. A *t* test comparing the endpoints (i.e., [b] versus [w] and [d] versus [j]) for both continua was performed to evaluate differences in performance. The *t* test revealed no significant difference between the performance of the children with CIs at the endpoint for the [bɑ] – [wɑ] continuum, t(6)= 1.082, p= .321. The children with CIs performance on the endpoints for the [bɑ] - [wɑ] continuum was respectively, 97% and 91%. The performance of the children with CIs on the [bɑ] – [wɑ] continuum did not support the auditory temporal deficit hypothesis. The *t* test for the [dɑ] – [jɑ] continuum revealed a significant difference in the performance at the endpoints, t(6)= 2.489, p= .047. However, the performance of the children with CIs on the [dɑ] – [jɑ] continuum was contradictory to the prediction in that they performed significantly better at the stop-end (93%) of the continuum compared to the glide-end (81%) of the continuum.
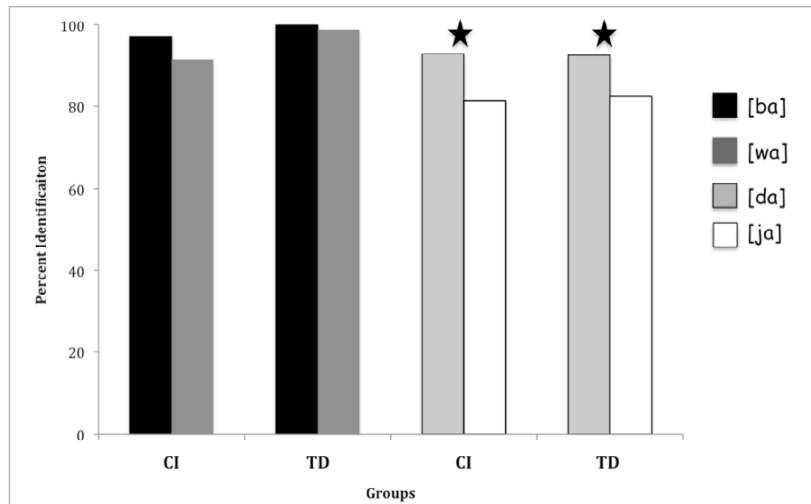
Figure 5: Typically-developing children and cochlear implanted children's performance on the endpoints of each continuum.
Note: ★ indicates significant difference in performance.

Evaluating the performance of the TD children revealed similar performance patterns compared to the children with CIs in that there was no significant difference in performance of the endpoints for the [bɑ] – [wɑ] continuum, t(7)= 1.00, p= .351 and there was a significant difference between in performance of the endpoints for the [dɑ] – [jɑ] continuum, t(7)= 2.65, p= .03. The TD children performance on the endpoints for the [bɑ] - [wɑ] continuum were respectively, 100% and 99% and for the [dɑ] – [jɑ] continuum, 92% and 82%. When comparing the endpoint performance of the children with CIs and TD children, the only difference in performance on the endpoints was [wɑ],

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t(13)= 2.13, p= .05. The TD children (99%) were significantly more accurate at identifying [wɑ] compared to the children with CIs (91%).

The performance of the children with CIs on the endpoints of both continua did not support the auditory temporal deficit hypothesis. They did not seem to have any difficulty processing the shorter transitions of the stops compared to the longer durations of the glides. On the [bɑ] – [wɑ] continuum there was no difference in performance between the two ends of the continuum. Furthermore, the performance of the children with CIs on the [dɑ] – [jɑ] continuum was opposite of what the auditory temporal deficit hypothesis predicted in that the children with CIs performed better at the stop end of the continuum compared to the glide end. It seems that the brevity of the transition does not play as prominent factor in speech perception of the stop and glide endpoints for children with CIs.

The third research hypothesis to be addressed was: If auditory sensitivity adversely impacts speech perception, then children with CIs will have shallower slopes and will have phonetic boundaries that occur closer to the glide-end of the continuum compared to TD children. There are differences in slopes on the [bɑ] – [wɑ] continuum between the children with CIs and the TD children. The slope provides information on how confidently one decides where the phonetic boundary exists between two phones: a higher value would be considered steeper compared to a slope with a smaller value (e.g., a slope of.569 is shallower than a slope of 1.068). There were significant differences on the slope of the [bɑ] – [wɑ] continuum between children with CIs and TD children,

F(1,20)= 25.382, p< .001. The children with CIs had shallower slopes compared to the

TD children, which supports our hypothesis that children with CIs are less confident in

defining the phonetic boundaries compared to TD children.

Participant	[ba-wa] slope	[ba-wa] boundary	[da-ja] slope	[da-ja] boundary
Children with Cochlear Implants				
CI01	.795	5.08	.361	5.83
CI02	.714	3.70	1.07	3.30
CI03	.458	4.62	.346	5.20
CI04	.699	4.17	.515	5.00
CI05	.683	5.46	.729	5.43
CI06	1.124	4.57	.559	3.72
CI07	.352	4.84	.258	5.22
Means	**.689**	**4.64**	**.548**	**4.81**
Typical Developing Children				
TD01	.826	3.93	.499	6.16
TD02	.914	2.88	.631	4.21
TD03	1.124	3.43	.528	3.98
TD04	1.124	3.43	1.65	2.83
TD05	1.046	3.24	.427	4.74
TD06	1.031	3.02	.611	3.70
TD07	1.645	3.00	.349	4.71
TD08	.575	4.92	.388	5.58
Means	**1.04**	**3.48**	**.635**	**4.49**
Adults				
Adult01	1.03	4.99	.870	4.90
Adult02	1.65	4.00	1.65	5.00
Adult03	1.24	4.5	1.05	4.24
Adult04	1.09	3.5	1.12	3.79
Adult05	1.05	3.24	.987	3.37
Adult06	.914	3.95	.710	4.00
Adult07	1.65	2.83	.839	4.69
Adult08	1.09	3.85	.734	3.16
Means	**1.21**	**3.86**	**.993**	**4.14**

Table 2: Individual performances for slope and phonetic boundaries

However, there was no difference in performance between the children with CIs and TD children on the slope of the [dɑ] – [jɑ] continuum, F(1,20)= 1.065, p= .316. Anecdotally, there was considerable variation in the performance of the children on the [dɑ] – [jɑ] continuum, which could have contributed to the non-significance finding for slope. The children with CIs were not as confident in defining the phonetic boundary on the [bɑ] – [wɑ] continuum compared to TD children, which suggests they have less defined phonological representation of these phonemes.

As seen in Figure 6, there is a clear difference in phonetic boundary on the [bɑ] – [wɑ] continuum between the children with CIs and the TD children. The children with CIs were in fact biased towards longer durations and their phonetic boundary on the [bɑ] – [wɑ] continuum was closer to the glide (4.64) compared to the TD children (3.48), which supports our predictions regarding the auditory sensitivity hypothesis.
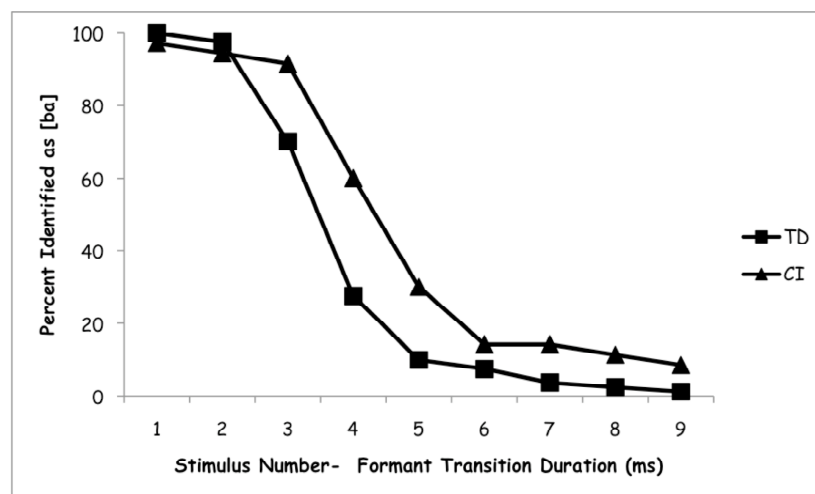

Figure 6: Typically-developing children compared to cochlear implanted children on the [bɑ-wɑ] continuum

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However, the performance on the [dɑ] – [jɑ] continuum did not support this prediction,

see Figure 7. The linear contrast for the [bɑ] – [wɑ] continuum revealed significant

differences in the phonetic boundary between children with CIs and TD children,

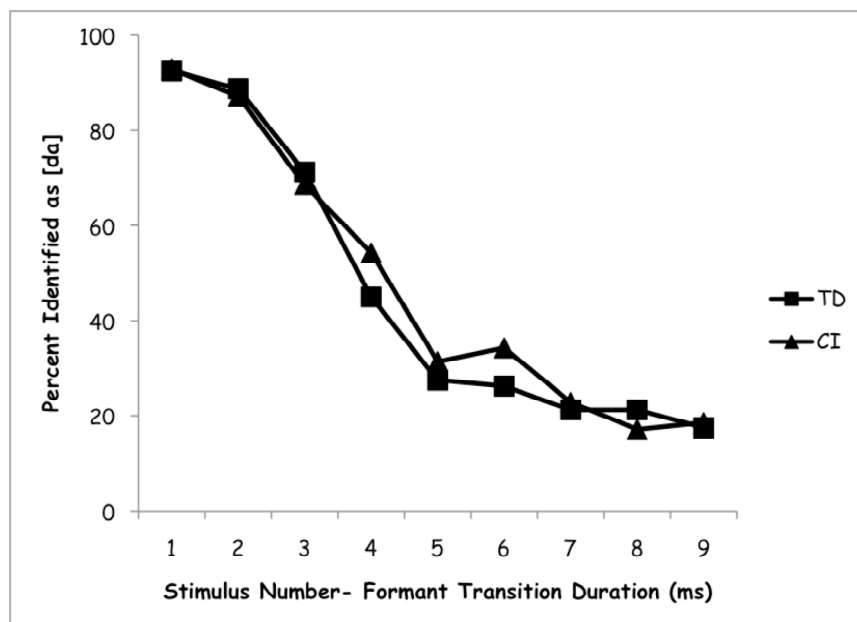F(1,20)= 52.811, p< .001. See Table 2 for individual data.

Figure 7: Typically-developing children compared to cochlear implanted children on the [da- ja] continuum

It is evident that children with CIs need longer formant transitions to switch from a stop

phoneme to a glide phoneme compared to TD children. This finding is similar to what is

observed in children with SLI (Burlingame et al., 2005). There are two possible reasons

to explain the performance of children with CIs. One explanation is that the performance

of the children with CIs might be a result of their hearing loss in that they need louder

and longer acoustic cues. Another explanation is that it could be children with CIs have

less defined phonological categories.

CHAPTER V

DISCUSSION

Previous research in the area of speech perception has consistently demonstrated developmental differences between children and adults. Therefore, it was expected that the TD children and children with CIs in this study would perform differently from the adults for phonetic boundary and slope on both continua. The performance of the TD children and children with CIs in fact supports developmental differences for both phonetic boundary and slope.

The phonetic boundary between both groups of children and adults was significantly different for the [bɑ] –[wɑ] continuum but not for the [dɑ]-[jɑ] continuum. Even though both continua increased in transition duration from a stop consonant to a glide consonant, the differences in temporal and spectral features between the phonemes in each continuum might have contributed to the difference observed in the performance between the two continua. In regards to the temporal features, the stop consonant [b] has a shorter voice onset time (~10ms) compared to the [d] voice onset time (~20 ms). Therefore, the perceptual difference between the consonants [b] and [w] might be perceived as greater compared to the perceptual difference between the consonants [d] and [j]. When examining the magnitude of the frequency change of F2, there is relativity

no difference between the continua such that the [bɑ] –[wɑ] continuum has a 550 hz

change and the [dɑ]-[jɑ] continuum has a 500 Hz change. Therefore, it can be assumed

that the magnitude of change in frequency of F2 did not contribute to the observed

perceptual difference between the continua. When examining the spectral features of the

continua, the [bɑ] –[wɑ] continuum is relatively lower in frequency with an F2 of 650 Hz

compared to the [dɑ]-[jɑ] continuum with an F2 of 1700 Hz, which might have

contributed to the differences in perception between the continua. It has been documented

that young children have more difficulty with perceiving and interpreting higher

frequency phones than lower frequency phones (Ohde & German, 2011; Sussman, 2001).

Since the [dɑ]-[jɑ] continuum has relatively higher frequency energy compared to the

[bɑ] –[wɑ] continuum it might be more difficult to process, which would explain the

perceptual differences observed between the two continua.

The observed differences between the children and adults for the slopes were

significant and robust. The children's slopes for both continua were shallower compared

to the adults. This suggests that children are less confident in defining the phonetic

category between the two phonemes. This is not surprising since children are not as

developed neurologically or linguistically as adults. Young children initially have very

defined phonetic categories in that they are likely to have less tolerance for slight

variations or changes in the perception of phones such as the variation in formant

transition duration in the [bɑ] – [wɑ] continuum of the current research. This would result

in a larger range of ambiguous responses (e.g., responses around the 50% mark) for the

children compared to the adults. This is because the stimuli in the middle of the continuum are less distinct compared to the end points. As children start to mature neurologically and linguistically they begin to have more tolerance within each phonetic category and allow variations.

Auditory Temporal Deficit Hypothesis in Children with Cochlear implants

The auditory temporal deficit hypothesis was developed to provide an explanation for language impairment in children with SLI. This hypothesis suggests that children with SLI have disproportionate difficulty discriminating and processing brief and/or rapidly changing speech stimuli such as the stop consonant in the continuum, which results in an auditory temporal disorder that interferes with the ability to form consistent mental representations of auditory stimuli (Tallal, 1990; Tallal et al., 1996). The results of the present study do not completely support the auditory temporal deficit hypothesis in children with CIs in that they did not perform worse at the stop-end of the continuum compared to the glide-end of the continuum. It might be that the abrupt changes in amplitude and spectral information of the stop-consonants provide ample acoustic information in identification, which would support the discontinuity hypothesis and previous findings from Guillot and Ohde (2010). In support of the auditory temporal deficit hypothesis, the children with CIs required longer duration cues such that their phonetic boundaries were shifted towards the glide end of the continuum for [bɑ]-[wɑ], compared to the TD children.

Another area to consider is the language abilities of the children with CIs in this study. It is well documented that children with CIs have delays in learning language. However, the children with CIs in the present study all had normal non-verbal cognitive abilities and six out of seven had standardized language scores within the normal range (i.e., 85 to 115). Children with SLI have marked difficulties learning language even though they have normal non-verbal cognitive abilities (Tomblin, 1991). When diagnosing a child with language impairment, a clinician will typically evaluate the child's non-verbal cognitive abilities in addition to their general (i.e., omnibus language measure) and specific (i.e., grammar or syntax) language abilities to determine if there is a discrepancy between ability (i.e., non-verbal cognition) and performance (i.e., language; Rice & Wexler, 1996; Tomblin, Records, & Zhang, 1996). A discrepancy is typically considered 1 to 1.5 standard deviations difference between the cognition and language measures. One of the exclusionary criteria for SLI is hearing loss therefore clinically a child with hearing loss could not be diagnosed with SLI. However, some children with hearing loss seem to have difficulty learning language despite early identification, amplification and intervention and normal non-verbal cognitive abilities.

Even though a majority of the children with CIs in this study have standard scores within the normal range for an omnibus language measure and receptive/expressive vocabulary measures, six out of seven children would be identified as having language-learning difficulties based on a discrepancy model. Additionally, as a group, the children with CIs performed approximately one standard deviation below the performance of the TD children on the language measures in the current study.

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The underlying cause of the language-learning difficulties in children with SLI and CIs might be rooted in the differences observed in speech perception between them and TD children. When investigating the speech perception of children with CIs, there has only been an emphasis on speech perception of words and sentences and not on speech perception of phones (Geers et al., 2003). It has been assumed that if age of identification and age of implantation are controlled, and the child receives suitable language and auditory experiences, then they will acquire language normally. However, there is the possibility that some children with CIs are not able to take maximum advantage of the auditory information provided by a cochlear implant. In fact, a large portion (50%) of children with CIs have language-learning difficulties, even though they have normal nonverbal cognition and early (i.e., prior to two years of age) identification of hearing loss, implantation, and intervention (Geers, 2002; Geers, Nicholas et al., 2003; Hawker et al., 2008; Inscoe et al., 2009). It might be that the hearing loss negatively impacts speech perception development, which in turn negatively impacts language development. Or it could be that some children with CIs have language-learning difficulties as seen in children with SLI in addition to their hearing loss.

Auditory Sensitivity and Speech Perception

Auditory sensitivity in this context refers to the type of hearing (i.e., normal hearing and cochlear implant) and the degree of hearing (i.e., although children with CIs usually have a severe-profound acoustic hearing loss, they typically have aided hearing thresholds around 20-25 dBHL). Children with CIs had shallower slopes and phonetic boundaries different from the TD children. The shallow slopes of the children with CIs indicate that they have reduced sensitivity or less consistency to the changing phonetic stimuli compared to the TD children. The children with CIs required longer durations to shift from the stop to the glide phoneme, whereas the TD children shifted sooner to the glide within the continuum. The performance of the children with CIs is comparable to that seen in children with SLI. There is evidence that children with SLI have poorer auditory discrimination and temporal processing (Elliott & Hammer, 1988; Leonard, et al., 1992) and poorly-defined phonetic categories, which are represented by shallower slopes and shifted phonetic boundaries on a phonetic continuum (Sussman, 1993, 2001) than TD children. This finding suggests that auditory sensitivity has an impact on speech perception such that if one has a disruptive or degraded auditory sensitivity, then it will adversely affect speech perception abilities. The children with CIs in the present study required longer formant duration cues (i.e., the phonetic boundary was shifted towards the glide) to switch categories from a stop to a glide compared to the TD children. The children with SLI in the Burlingame et al. (2005) study also had boundaries that were closer to the glide-end of the continuum.

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It is unclear as to the reason why children with cochlear implants require longer durations compared to TD children. There are three possible explanations as to why children with CIs need longer durations. The first possible explanation could be they have delayed speech perception such that they would perform similar to younger TD children. Children who use cochlear implants have had some degree of auditory disruption, which could have caused auditory deprivation. Auditory deprivation negatively impacts neurological development of the auditory pathways, which then negatively impacts development of speech perception. It could be that the children with CIs are just delayed in their speech perception abilities and might perform similar to younger children with normal hearing. It could be that the children with CIs in this study need more auditory maturation so that they eventually catch up to TD children. The scope of this study did not include a younger group of TD children to explore this explanation. A future study investigating this notion is warranted.

The second possible explanation could be that children with CIs have disordered speech perception such that they might never have comparable speech perception abilities of their TD peers much like what is seen in children with SLI. However, the origin of the disorder between children with CIs and children with SLI would be different. Children with CIs receive auditory information via electrical stimulation from their cochlear implant. The difference in how children with CIs process the auditory signal might fundamentally impact how they perceive and process speech at the phoneme level. One way to further explore this notion is to compare children with CIs to children who use

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hearing aids and see if the differences in speech perception are due to hearing loss or cochlear implant processing.

The third possible explanation could be that children with CIs have both delayed and disordered speech perception in that they might look like younger TD children but never perform comparable to peers on speech perception tasks. It might be that auditory deprivation causes not only a delay in auditory development but also a disruption in the auditory system that results in long-term deficits in perception and language development. It could be that children with CIs will always perform differently from TD peers due to the differences in the hearing mechanism and continually require longer durations. There is evidence to support that children with CIs have difficulty processing short durations (e.g., 50 ms) compared to TD children of the same age and younger (Guillot, Ohde & Hedrick, in prep). Rice and colleagues (1991) have used the delay and disordered explanation to describe impaired language abilities, specifically grammar in children with SLI.

In summary, there is evidence that a developmental difference exists between TD children and adults in perception of formant duration changes on two stop-glide continua. The TD children were sensitive to formant transition changes in the [bɑ] – [wɑ] continuum and had shallower slopes for both continua compared to the adults. The children with CIs required longer durations to transition from the stop to the glide compared to TD children and adults. There is evidence that a degraded auditory sensitivity negatively impacts speech perception abilities such that the children with CIs had shallower slopes and different phonetic boundaries compared to TD children.

Implications and Future Directions

This study provides evidence that children with CIs perform differently than TD children who are age-matched on stop-glide continua. However, more questions need to be asked to understand the role hearing loss has on speech perception and language development. A limitation to the present study is that there was not a younger (e.g., 3.5-4-years-old) and older (e.g., 10 – 12-years-old) TD group of children. By having younger and older TD children, this would have provided not only more information regarding the trajectory of typical development, but would have also provided insight into the development of children with CIs. If the children with CIs performed similarly to the younger TD children, then it could be assumed that they are delayed in their performance and perhaps not disordered. Or if the children with CIs performed differently from the younger and older TD children, then it could be assumed that their speech perception does not follow the typical trajectory of development. It could be that the poor auditory sensitivity from hearing loss has an adverse impact on speech perception development that is not resolve over time. Therefore it would be valuable to conduct a longitudinal study that follows the speech perception and language development of both children with CIs and TD children. This would allow for the generation of growth curves of individual children as opposed to a cross-sectional study.   Additionally, it would also allow the evaluation of the relationship between the development of speech perception and language.

Another limitation of the present study is that there were only children with CIs in the study and not children with hearing aids so it is unclear as to if the difference in

speech perception was due to poor auditory sensitivity or the cochlear implant. One way to evaluate the impact of poor auditory sensitivity (i.e., hearing loss) would be to compare the performance of children with CIs to that of children with hearing aids on measures of speech perception. This would allow for the exploration of the different amplification and how it impacts speech perception.

A final limitation of the present was that there were not enough children to explore the correlation between speech perception and language abilities. One way to examine how speech perception related to language abilities is to look at the relationship between the slope and receptive vocabulary. The rationale for using the slope values as opposed to the phonetic boundary values is that the slope provides information regarding the confidence in labeling phonemes into two phonetic categories, whereas the phonetic boundary provides information regarding where a child responds with 50% accuracy. The slope provides information regarding the overall function of categorizing the phonemes. The rationale for using receptive vocabulary is that it is linked to lexical representation and density, which might be associated with speech perception of phones. Lexical representation and density refers to the similarity between words within an individual's lexicon that can be specifically defined as words that differ by one phone substitution, addition or deletion (e.g., "cat" would include "bat", "cap", "pat" among others; Charles-Luce & Luce, 1990). A young child who has a small lexicon requires only a global or gross-grain level of detail to differentiate adequately between lexical items. The early lexicons of children are not diverse or dense enough to cause confusion between words. As the child's lexicon grows and becomes denser, a fine-grain level of detail is needed to

make distinctions between lexical items. One's speech perception abilities might be related to the size of one's receptive vocabulary such that a child with better speech perception will have a higher standard score on the receptive vocabulary measure or vise versa. It is predicted that receptive vocabulary will be stronger correlated to the slope compared to the general language abilities.

A preliminary exploration between receptive vocabulary (i.e., PPVT) and slope on the [bɑ] – [wɑ] and [dɑ] - [jɑ] continua revealed a marginal positive correlation r= 0.324 and r= 0.481, respectively. The relationship seems to be stronger for the [dɑ] - [jɑ] continuum compared to the [bɑ] – [wɑ] continuum, which might be related to the perceptual difficulty of the [dɑ] - [jɑ] continuum. To adequately explore the relationship between speech perception and receptive vocabulary, one would need a larger age range and number of children. Based on this preliminary finding in the present study, it is predicted that there would be a strong positive correlation between slope and receptive vocabulary with increased number of children.
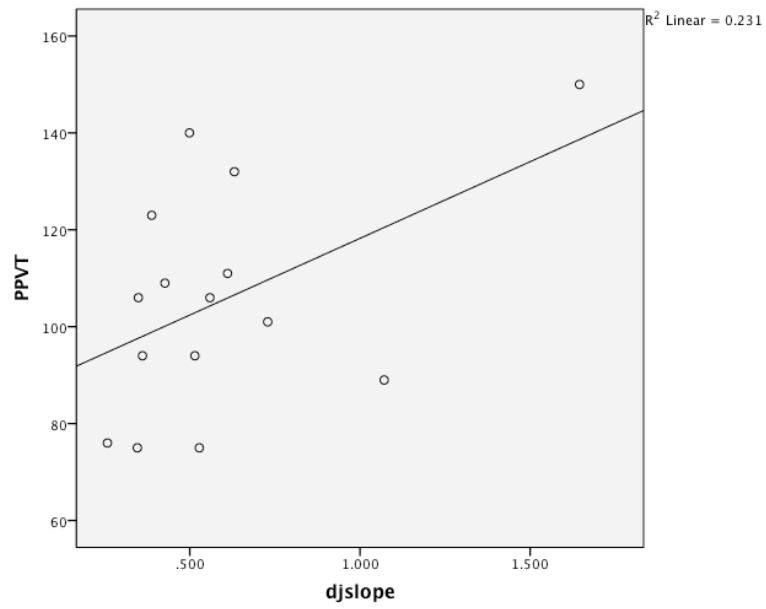
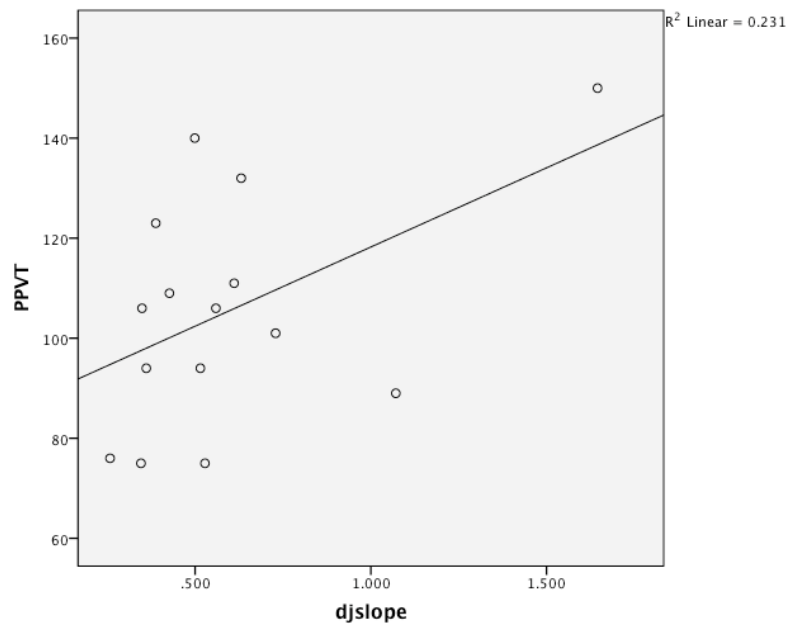Figure 8: Correlation between Peabody Picture Vocabulary Test score and the slope of [bɑ-wɑ] for all children

Figure 9: Correlation between Peabody Picture Vocabulary Test score and the slope of [dɑ-jɑ] for all children

Conclusion

In conclusion, the current research focused on three research hypotheses that addressed aspects of typical and atypical development of speech perception on two formant transition continua. This research supported typical and atypical developmental effects of speech perception on formant transition continua in that TD children perform differently than adults and children with CIs perform differently from TD children. Results indicated that:

1) Typically-developing children had greater perceptual variability such that they had shallower slopes for both continua compared to the adults.

2) Typically-developing children were sensitive to formant transition durations such that they identified more of the stimuli as glides compared to the adults, as predicted by the cue weighting shift hypothesis.

3) The performance of children with CIs partially supported the auditory temporal deficit hypothesis in that they required longer formant transitions durations compared to the TD children. However, the children with CIs did not perform worse at the stop-end of the continuum compared to the glide-end of the continuum, as predicted by the auditory temporal deficit hypothesis.

4) Degraded or poor auditory sensitivity negatively impacts speech perception in that children with CIs have significantly shallower slopes and shifted phonetic boundaries compared to TD children.

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